NASA/TM—2001-211318

IEPC–01–280

Preliminary Results of Field Emission Cathode Tests

James S. Sovey
Glenn Research Center, Cleveland, Ohio

Scott D. Kovaleski
QSS Group, Inc., Cleveland, Ohio

December 2001

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2001-211318 IEPC–01–280

Preliminary Results of Field Emission Cathode Tests

James S. Sovey
Glenn Research Center, Cleveland, Ohio

Scott D. Kovaleski
QSS Group, Inc., Cleveland, Ohio

Prepared for the
27th International Electric Propulsion Conference
cosponsored by the AFRL, CNES, ERPS, GRC, JPL, MSFC, and NASA
Pasadena, California, October 14–19, 2001

National Aeronautics and
Space Administration

Glenn Research Center

December 2001

Acknowledgments

The authors wish to acknowledge the assistance and technical support provided by Patrick P. Barber in the operation and setup of the vacuum facility. The authors also wish to acknowledge GENVAC Aerospace Corporation for supplying the CVD diamond coupons.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

Preliminary Results of Field Emission Cathode Tests

James S. Sovey
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135
Phone: 216–977–7454, Email: James.Sovey@grc.nasa.gov

Scott D. Kovaleski
QSS Group
Cleveland, Ohio 44135

Preliminary screening tests of field emission cathodes such as CVD diamond, textured pyrolytic graphite, and textured copper were conducted at background pressures typical of electric thruster test facilities to assess cathode performance and stability. Very low power electric thrusters which provide tens to hundreds micronewtons of thrust may need field emission neutralizers that have a capability of tens to hundreds of microamperes. From current voltage characteristics, it was found that the CVD diamond and textured metals cathodes clearly satisfied the Fowler-Nordheim emission relation. The CVD diamond and a textured copper cathode had average current densities of 270 $\mu A/cm^2$ and 380 $\mu A/cm^2$, respectively, at the beginning-of-life. After a few hours of operation the cathode emission currents degraded by 40 to 75 percent at background pressures in the 10^{-5} Pa to 10^{-4} Pa range. The textured pyrolytic graphite had a modest current density at beginning-of-life of 84 $\mu A/cm^2$, but this cathode was the most stable of all. Extended testing of the most promising cathodes is warranted to determine if current degradation is a burn-in effect or whether it is a long-term degradation process. Preliminary experiments with ferroelectric emission cathodes, which are ceramics with spontaneous electric polarization, were conducted. Peak current densities of 30 mA/cm^2 to 120 mA/cm^2 were obtained for pulse durations of about 500 ns in the 10^{-4} Pa pressure range.

Introduction

Electric thrusters with input power levels from 1 W to about 100 W need electron emitters that require very low gas flow rates or no gas flow to perform their functions efficiently. In order to ensure that very low-power colloid thrusters, Field Emission Electric Propulsion (FEEP) devices, ion engines, Hall-effect thrusters, and gridded vacuum arc thrusters are reasonably attractive systems, a field-emission neutralizer is certainly desirable [1–6]. The Field Emission Cathode (FEC) is potential candidate to replace hollow cathodes and other thermionic emitters as cathodes for electric thrusters, spacecraft plasma contactors, and electrodynamic tether systems. FECs are generally comprised of two types, namely, the Spindt cathode which are cone-like structures and also coatings that have a negative electron affinity (NEA). The NEA coatings are usually carbon-based materials that might be doped with nitrogen, boron, hydrogen, or cesium. A recent review of the FEC technology as it relates to electric thrusters and their basic requirements can be found in Reference 7. For example, the very low power FEEP and colloid thrusters which provide tens to hundreds micronewtons of thrust will require neutralizers that have a capability of tens to hundreds of microamperes. FECs have already demonstrated emission currents up to tens of mA/cm^2 in ultra-high vacuum environments [7]. Over the last few years researchers have been examining the Spindt type cathodes [8], diamond-film cathodes [9], and carbon nanotube cathodes [10] for electric propulsion applications. Although initial results sometimes look promising, operation of some of the FECs in traditional electric thruster test environments usually results in the degradation of emission current with time. Operation in test chambers with oxygen, nitrogen, water, or xenon at partial pressures of 10^{-6} to 10^{-5} Pa usually causes loss of performance over time [8].

This paper reports on preliminary screening tests of FECs, which use chemical vapor deposited (CVD) diamond, textured pyrolytic graphite, ion-beam textured copper, and untextured metals. The field emission properties of ferroelectric ceramics are also examined. Goals for the series of experiments include obtaining current densities greater than 10 mA/cm^2 with electric fields less than 25 V/μm. FECs with this emission current capability would satisfy requirements for electric thrusters operating at many tens of watts. Very short-term evaluations of FEC emission current stability were conducted at rather high facility background pressures of 10^{-5} to 10^{-4} Pa, which is typical of electric propulsion test facilities. At these background pressures one would expect to have significant partial pressures of water, nitrogen, oxygen, carbon dioxide, hydrogen, and argon. Some of these gases may lead to changes in cathode surface chemistry and in field emission characteristics [8]. The quantification of vacuum facility atmospheric composition is left to future work. All cathodes were tested in a simple diode configuration.

Apparatus and Procedure

Preparation of Cathode Materials

As indicated in Table 1 there are three reference cathode materials namely, copper, pyrolytic graphite, and AISI O-1 low alloy tool steel. These three cathode materials have surface finishes in the range of 0.1 μm rms to 2.3 μm rms. Note that ground and polished surfaces have surface finishes of about 0.8 μm rms and 0.1 μm rms, respectively. Data from these materials serve as a baseline or reference. The materials of interest are CVD diamond, ion beam textured pyrolytic graphite, and ion beam textured copper. All substrates were washed in acetone and then ethyl alcohol prior to texturing or coating.

The diamond film on a molybdenum substrate was processed using hot-filament CVD. The 2.54×3.81× 0.13 cm molybdenum substrate was held at 800 °C. A gas mixture composed of 2% methane and 98% hydrogen was directed at a hot filament to stimulate the CVD process [11,12]. The diamond film thickness is approximately 4 μm.

Figure 1a is an illustration the apparatus used to texture the pyrolytic graphite (PG) [13]. The PG naturally textures when sputtered by the ion beam. A 30 cm diameter argon ion source was used [14], the PG was placed 15 cm downstream. The ion energy was 1000 eV, and the average ion current density at the ion source was 2.2 mA/cm^2. Ion etch time was 2 hours 11 minutes. The resulting surface structures are spires with heights of about 10 μm separated by about 4 μm. Figure 2a is a photomicrograph of typical texture on the ion beam processed PG. The textured surface appears black versus the gray color of the original PG.

Figure 1b shows the seed texturing process [13] used for the two textured copper coupons. A tantalum target was located at 45 degrees with respect to the 30 cm diameter ion source centerline as shown in Figure 1b. For the Textured Copper-C coupon, a 15 cm by 15 cm target was translated so the downstream edge was 20 cm below the centerline and 15 cm from the ion source. The copper coupon was located on centerline and 15 cm from the ion source. The argon ion energy was 1000 eV, and the average ion current density at the ion source was 2.1 mA/cm^2. The ion sputtering time in this case was 16 hours. Only wide-angle ions struck the tantalum seed target, so the tantalum arrival rate at the copper coupon was very low. The low seed arrival rate at the coupon and the operating conditions produced cones, on the copper surface, with diameters of about 12 μm and cone-heights of about 17 μm. Figure 2b is a photomicrograph of typical texture on the Textured Copper-C coupon. The color of this coupon is dark orange.

For the Textured Copper-S coupon, the target was translated so the downstream edge was about 7 cm below the centerline and 15 cm from the ion source. The copper coupon was located on centerline and 15 cm from the ion source. The argon ion energy was 1000 eV, and the average ion current density at the ion source was 3.1 mA/cm^2. The ion sputtering time in this case was 15 minutes. The tantalum arrival rate at the copper coupon was relatively high compared to the Textured Copper-C coupon. The high seed arrival rate at the coupon and the operating conditions produced closely packed spire-like structures on the copper surface with diameters estimated to be 1 μm or less. The color of the Textured Copper-S coupon was black.

Configuration of the Electrodes

Field emission measurements were made in a simple diode configuration consisting of a stack comprised of

a steel cathode base, a coupon at cathode potential, a polyimide spacer(s), and a steel anode. The stack was held in place using an insulated clamp. The steel anode was 2.54×3.81×0.32 cm, and the steel cathode base was made longer (2.54×6.35×0.32 cm) for handling purposes. Ground steel was selected for the electrode material because it had a reasonably smooth surface finish. The areas of the cathode coupons are identified in Table 1. The polyimide spacers were approximately 120 μm thick and were used to insulate the anode from the coupon/cathode electrode. The steel electrodes were drilled and tapped for terminating wires for the electrical circuit.

Test Facility and Instrumentation

Cathode tests were performed in a cryogenically-pumped bell jar with an ultimate pressure of 4×10^{-6} Pa. The cathode/anode assembly was mounted in a 0.3 m diameter test port attached to the bell jar. A 0.3 m pneumatic gate valve provided isolation of the bell jar and the test port during equipment changes. With the gate valve open, the test port/bell jar system pressure was usually less than 5×10^{-5} Pa.

Power to the diode arrangement was provided by a 5 kV, 25 W power supply. A current limiting resistor of 100 kΩ was also in the electrical circuit. Current monitoring was made using an electrometer capable of measuring to tens of picoamperes.

Results and Discussion

The Fowler-Nordheim Relation

Field emission is described as electrons tunneling through a potential barrier at the surface of a solid when a large electric field is applied. Knowing some of the surface properties, one can calculate the probability of an energetic electron tunneling through the potential barrier [15]. The electron field emission can be expressed by the Fowler-Nordheim (F-N) equation. For a given electrode separation and material work function, the following equation results for the current density.

$$J = aV^2 \exp\left(-\frac{b}{V}\right) \qquad (1)$$

where V is the applied voltage and a, b are constants. In Figure 3 the CVD diamond and Textured Copper-C data are plotted in the Fowler-Nordheim coordinates. The linearity of the plots indicate the data satisfy the F-N field emission relation.

Comparison of Field Emission Data

Figure 4 displays the field emission characteristics of the seven cathode materials. The reference materials copper, pyrolytic graphite, and steel had emission current densities of 30 μA/cm^2 or less. The textured pyrolytic graphite cathode had a current density of 84 μA/cm^2 and was stable over its first few hours of operation at 4×10^{-5} Pa background pressure. The textured pyrolytic graphite cathode was the most stable of all cathodes at the beginning-of-life. Extended operation of the cathodes was beyond the scope of this work. The CVD diamond and Textured Copper-C cathodes had maximum current densities of about 270 μA/cm^2 and 380 μA/cm^2, respectively. Both cathodes exhibited degradation of emission current during the first few hours of operation. The Textured Copper-S cathode current density was in the 0.9 to 2.3 μA/cm^2 range. These values are much lower than the untextured copper cathode current density. Reasons for this result are unknown to the author and await more detailed scanning electron microscope and energy dispersive X-ray analysis of this cathode material.

Figures 5 shows the CVD diamond cathode emission current versus applied voltage. There was a 75% reduction in emission current after operation at ~ 10^{-4} Pa for about 4 hours. If the turn-on electric field is defined to be the applied field required to yield an emission current of 1 nA, then the turn-on electric field at beginning-of-life was 2.1 V/μm and four hours later it was 6.2 V/μm. Both of these results indicate there were significant changes in surface chemistry and/or surface structure.

Other investigators have had results that exhibited more stable emission currents when CVD diamond cathodes are operated at pressures in the 10^{-5} Pa to 10^{-6} Pa range [12]. In this example, a CVD diamond cathode operated for one hour with current fluctuations of 5% at the average current density of 330 μA/cm^2. The applied field was 18 V/μm. Total operating time was omitted.

Cathode emission current versus applied voltage for the Textured Copper-C cathode is shown in Figure 6.

After one hour of testing, the emission current degraded by 30% to 40% for applied fields in the 7.6 V/μm to 8.0 V/μm range. The turn-on electric field was in the 3.2 V/μm to 3.4 V/μm range at beginning-of-life and one hour later. Extended tests need to be performed on this cathode to determine if the current degradation at higher electric fields is a burn-in effect or whether it is part of a long-term degradation process at background pressures of about 5×10^{-5} Pa.

Large Area Field Emitter Performance Comparisons

Table 2 compares the performance of a few large area, molybdenum and carbon-based FECs [7,16–19]. Some of the vacuum processed diamond and carbon nanotube FECs have demonstrated current densities ≥ 90 mA/cm^2 at applied fields 5.5 V/μm to 11 V/μm. Molybdenum tipped FECs have also operated at tens of mA/cm^2. To the best of the author's knowledge these FECs have not demonstrated stable, long-term operation in facilities with background pressures in the 10^{-2} Pa to 10^{-5} Pa range where water, oxygen, and nitrogen are present.

At lower current densities, carbon nanotubes [18] and laser-ablation processed diamond [19] have demonstrated stable emission at facility pressures of 10^{-4} Pa to 10^{-3} Pa for periods up to 25 hours. FECs run at low power stress or derated conditions have exhibited more stable emission [20]. In this case a carbon nanotube FEC was stable for one hour when a 13 V/μm field was applied. When the applied field was increased to 37 V/μm, the power stresses were sufficiently high to cause the emission current to degrade to nearly 10% of its initial value within one hour.

The CVD diamond FEC suffered a degradation in emission current of about 25% in a one-hour test independent of whether it was run at an applied field of 17 V/μm or 10 V/μm. For this CVD diamond FEC, derating performance is an inadequate solution for operation above 10^{-5} Pa. The Textured Copper-C also had emission current degradation of 30 to 40% after only one hour of testing at ~ 8 V/μm and a background pressure of 5×10^{-6} Pa. The textured pyrolytic graphite cathode had a current density of 84 μA/cm^2 and was the most stable of all cathodes at the beginning-of-life. The textured PG cathode emission current remained within ± 7% of its average value for its first 1.5 hours of operation at a background pressure of 4×10^{-5} Pa and an applied field of 8V/μm. Extended testing of this material, although it has a modest field emission current density, appears warranted.

Another Cathode Option: Ferroelectric Emission Cathodes

A program to study ferroelectric emission (FEE) cathodes has recently been initiated at the NASA Glenn Research Center as an alternative expellantless cathode. Ferroelectrics are ceramics with a spontaneous electric polarization. Ferroelectric emission refers to the pulsed emission of electrons from ferroelectric ceramic materials [21]. If a large, fast rise-time, pulsed electric field is applied across a ferroelectric ceramic such that it opposes the spontaneous polarization, the ceramic will emit electrons. The electric field is generated by applying a high voltage pulse between a solid electrode on one side of the ferroelectric and a gridded electrode on the opposite, electron-emitting side. Electron emission of up to 100's of A/cm^2 over a pulse length of hundreds of nanoseconds has been observed [21].

FEE cathodes are being considered for reasons of simplicity and durability. The cathodes are capable of operating in background pressures up to 10 Pa and in impure environments. FEE cathodes have been run at 100 to 200 Hz for 10^6 shots (approximately 2 hours) [22]. Cathodes run in gun geometries reportedly show little evidence of cathode damage and longer lives [23]. Since it has been reported that the cathodes can run with low, or no, electron extraction voltages, the concept appears to mitigate ion sputtering life limiting mechanisms of FECs. Since FEE cathodes are cold cathodes, they should not be subject to the limitations physical evaporation places on thermionic cathodes. A ferroelectric emission cathode system is expected to be simple and compact. The cathode itself is essentially a capacitor, and thus is easily fabricated.

Electron current has been extracted from ferroelectrics in initial experiments at NASA GRC. Figure 7 shows a simple schematic of the FEE cathode assembly. The anode to grid separation distance was about 2 mm, the ferroelectric ceramic thickness was 1 mm, and the diameter was 2 cm. The ferroelectric tested was lead zirconate titanate (PZT). Rectangular, unipolar, high-voltage pulses of approximately -830 to -930 V were applied to the rear of the ceramic. Current was collected at the anode with anode voltage of 50 to

100 V. From Figure 8, the cathode was capable of emitting approximately 100 mA to 400 mA peak currents for a pulse duration of approximately 500 ns. This corresponds to peak current densities of 30 mA/cm^2 to 120 mA/cm^2. Facility pressure was 4.8×10^{-4} Pa. The high-voltage pulse threshold for electron emission was found to be approximately -700 V. Given the preliminary nature of the results presented here, it is anticipated that larger current densities at higher repetition rates can be realized, yielding high average current.

Concluding Remarks

Preliminary screening tests of field emission cathodes such as CVD diamond, textured pyrolytic graphite, and textured copper were conducted at background pressures typical of electric thruster test facilities to assess cathode performance and stability. At these background pressures one would expect to have significant partial pressures of water, oxygen, nitrogen and carbon dioxide. These gases may lead to changes in cathode surface chemistry and in the field emission characteristics.

From current voltage characteristics, it was found that the CVD diamond and textured metals cathodes clearly satisfied the Fowler-Nordheim emission relation. The CVD diamond and Textured Copper-C cathode had average current densities of 270 μA/cm^2 and 380 μA/cm^2, respectively, at the beginning-of-life. After a few hours of operation the CVD diamond and textured copper cathode emission currents degraded by 75 and 40%, respectively, at background pressures in the 10^{-5} Pa to 10^{-4} Pa range. The textured pyrolytic graphite had a moderate current density at beginning-of-life of 84 μA/cm^2, but this cathode was the most stable of all. Its emission current variation was ± 7% about the average current for the first 1.5 hours of operation at 4×10^{-5} Pa and an applied field of 8 V/μm. Extended testing of the most promising cathodes is warranted to determine if current degradation is a burn-in effect or whether it is a long-term degradation process due to the relatively high facility background pressures. Quantification of vacuum facility atmospheric composition is also left to future work.

Preliminary experiments with ferroelectric emission cathodes, which are ceramics with spontaneous electric polarization, have been conducted. Peak current densities of 30 mA/cm^2 to 120 mA/cm^2 have been obtained for a pulse duration of about 500 ns in the 10^{-4} Pa pressure range. Future work with the FEE cathodes will examine additional materials and high repetition rates which will likely lead to higher current levels.

References

[1] Martinez-Sanchez, M., de la Mora, Fernandez, Hruby, V., Gamero-Castano, M., and Khayms, V., "Research on Colloid Thrusters," IEPC Paper 99-014, October 1999.

[2] Fehringer, M., Rudenauer, F., and Steiger, W., "Micronewton Indium Ion Thrusters," IEPC Paper 99-072, October 1999.

[3] Marcuccio, S., Paita, L., Saviozzi, M., and Andrenucci, M., "Flight Demonstration of FEEP on a Get Away Special," AIAA Paper 98-3332, July 1998.

[4] Patterson, M.J., Domonkos, M.T., Foster, J.E., Haag, T.W., Mantenieks, M.A., Pinero, L.R., Rawlin, V.K., Sarver-Verhey, T.R., Soulas, G.C., Sovey, J.S., and Strzempkowski, E., "Ion Propulsion Development Activities at NASA Glenn Research Center," AIAA Paper 2000-3810, July 2000.

[5] Jacobson, D.T. and Jankovsky, R.S., "Test Results of a 200 W Class Hall Thruster," AIAA Paper 98-3792, 1998.

[6] Anders, A., Schein, J., Qi, N., "Pulsed Vacuum-Arc Ion Source Operated with a Triggerless Arc Initiation Method," *Review of Scientific Instruments*, Vol. 71, No. 2, Pt. 1-2, February 2000, pp. 827-829.

[7] Marrese, C.M., "A Review of Field Emission Cathode Technologies for Electric Propulsion Systems and Instruments," *Aerospace Conference Proceedings, 2000 IEEE*, Vol. 4, pp. 85-98.

[8] Marrese, C.M. and Polk, J.E., "Molybdenum Field Emission Array Cathode Performance in Primarily Xenon Environments: Preliminary Experimental Results at Low Operating Voltages," AIAA Paper 2000-3266, July 2000.

[9] Tolt, Z.L., Fink, R.L., and Yaniv, Z., "Electron Emission from Patterned Diamond Flat Cathodes," *Journal of Vacuum Science and Technology B*, Vol. 16, No. 3, May/June 1998, pp. 1197-1198.

[10] Gamero-Castano, M., Hruby, V., Falkos, P., Carnahan, D., and Ondrusek, B., "Electron Field Emission from Carbon Nanotubes, and its Relevance in Space Applications," AIAA Paper 2000-3263, July 2000.

[11] Gupta, S., Weiss, B.L., and Morell, G., "Study of the Electron Field Emission and Microstructure Correlation in Nanocrystalline Carbon Thin Films," *J. of Applied Physics*, Vol. 89, No. 10, May 15, 2001, pp. 5671-5675.

[12] Zhu, W., Kochanski, G.P., Jin, S., and Seibles, L., "Electron Field Emission from Chemical Vapor Deposited Diamond," *J. of Vacuum Science and Technology, B*, Vol. 14, No. 3, May-June 1996, pp. 2011-2019.

[13] Banks, B.A., "Topography: Texturing Effects," Handbook of Ion Beam Processing Technology, J.J. Cuomo and S.M. Rossnagel, editors, Noyes Publications, Park Ridge, NJ, 1989, pp. 338-361.

[14] Sovey, J.S., "Characteristics of a 30-cm Diameter Argon Ion Source," AIAA Paper 76-1017, November 1976.

[15] Temple, D., "Recent Progress in Field Emitter array development for High Performance Applications," *Materials Science and Engineering*, Vol. R24, No. 5, January 25, 1999, pp. 184-239.

[16] Tolt, Z.L., Fink, R.L., and Yaniv, Z., "Electron Emission from Patterned diamond Flat Cathodes," *J. of Vacuum Science and Technology B*, Vol. 16, No. 3, May-June 1998, pp. 1197-1198.

[17] Gamero-Castano, M., Hruby, V., Falkos, P., Carnahan, D., and Ondrusek, B., "Electron Field Emission from Carbon Nanotubes and its Relevance in Space Applications," AIAA Paper 2000-3263, July 2000.

[18] Kwo, J.L., Yokoyama, M., Wang, W.C., Chuang, F.Y., and Lin, I.N., "Characteristics of Flat Panel Display Using Carbon Nanotubes as Electron Emitters," *Diamond and Related Materials*, Vol. 9, 2000, pp. 1270-1274.

[19] Busta, H.H. and Pryor, R.W., "Performance of Laser Ablated, Laser Annealed BN Emitters Deposited on Polycrystalline Diamond," *J. of Vacuum Science and Technology B*, Vol. 16, No. 3, May-June 1998, pp. 1207-1210.

[20] Tamtair, F.G., Chen, L.C., Wei, S.L., Hong, W.K., Chen, K.H., and Cheng, H.C., "High Current Density Field emission from Arrays of Carbon Nanotubes and Diamond-Clad Si Tips," *J. of Vacuum Science and Technology B*, Vol. 18, No. 3, May-June 2000, pp. 1207-1211.

[21] Rosenman, G., Shur, D., Krasik, Ya. E., and Dunaevsky, A., "Electron Emission from Ferroelectrics," *J. of Applied Physics*, Vol. 88, 2000, pp. 6109-6161.

[22] Einat, M., Shur, D., Jerby, E., and Rosenman, G., "Lifetime of Ferroelectric $Pb(Zr,Ti)O_3$ Ceramic Cathodes with High Current Density," *J. of Applied Physics*, Vol. 89, 2001, pp. 548-552.

[23] Nation, J.A., Schachter, L., Mako, F.M., Len, L.K., Peter, W., Tang, C., and Srinivasan-Roa, T., "Advances in Cold Cathode Physics and Technology," *Proceedings of the IEEE*, Vol. 87, 1999, pp. 865-889.

Table 1. Field emission cathode characteristics.

Cathode identification	Cathode area, cm^2	Surface preparation other than chemical cleaning	Surface characteristics	Cathode to anode separation, μm
Steel	1.0 to 2.2	None	0.1-0.7 μm rms surface finish	250
Pyrolytic graphite	1.2	None	2.3 μm rms surface finish	250
Textured pyrolytic graphite	1.0	Ion beam etched	Spires with heights of 6-12 μm and spacings of 3-6 μm	250
CVD diamond	5.0	Hot filament CVD, 2% CH_4, 98% H_2, 800 °C substrate	3 μm-5 μm coating on molybdenum	120
Copper	1.5	None	1.4 μm rms surface finish	250
Textured Copper-S	2.2	Ion beam textured using tantalum "seed material"	Submicron diameter spires	250
Textured Copper-C	2.2	Ion beam textured using tantalum "seed material"	Cones with bases of 10-15 μm and heights of 15-20 μm	250

Table 2. Large area field emitter performance comparisons.

Material	Emitter area, cm^2	Applied field, V/μm	Emission current density, mA/cm^2	Stable operation demonstrated at 10^{-2} to 10^{-5} Pa?	Reference
Molybdenum tips	0.0078	100	38	No	7
Vacuum-processed diamond	4.9	11	90	No	16
Carbon nanotubes	0.02 to 0.08	5.5	100	No	17
Carbon nanotubes	--	3	0.4	Yes, at 7×10^{-5} Pa	18
Boron nitride - diamond	0.002	42	0.5	Yes, up to 2×10^{-3} Pa	19
CVD diamond	5.0	16	0.07 to 0.27	No	This paper
Textured Copper-C	2.2	8	0.23 to 0.39	No	This paper
Textured pyrolytic graphite	1.0	8	0.07 to 0.08	Yes, at 4×10^{-5} Pa (short term test)	This paper

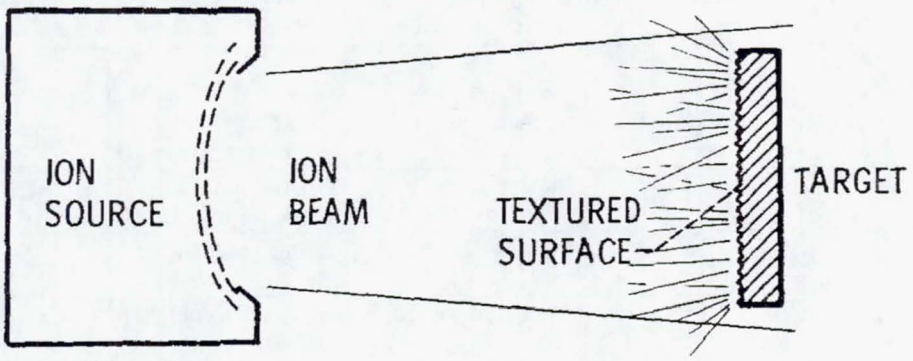

Figure 1a – Illustration of natural texturing of a target by an ion beam as was done with the textured pyrolytic graphite.

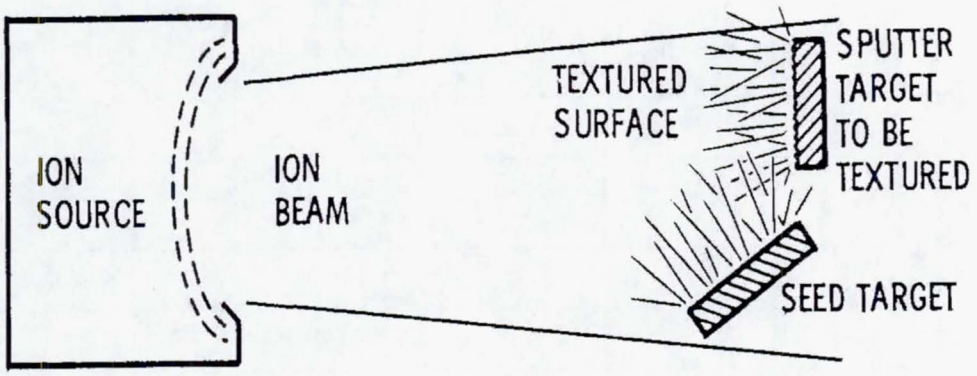

Figure 1b – Illustration of texturing of the copper coupons using "tantalum seed texturing."

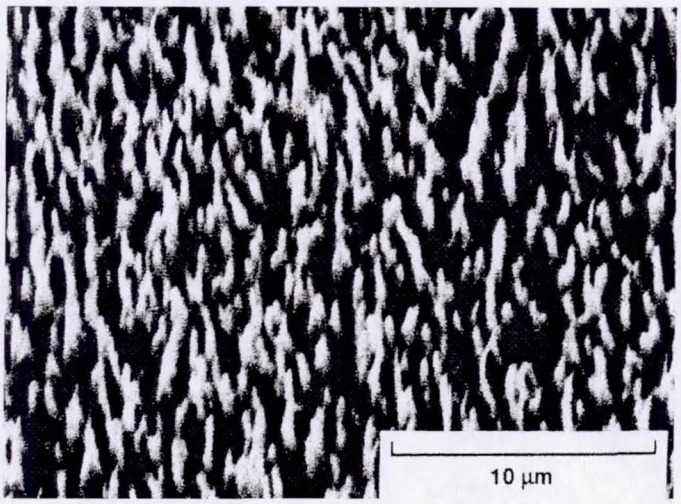

Figure 2a – Typical surface structure of the ion beam textured pyrolytic graphite. The structure is composed of sharp spires with heights and spacings of 6 μm to 12 μm and 3 μm to 6 μm, respectively.

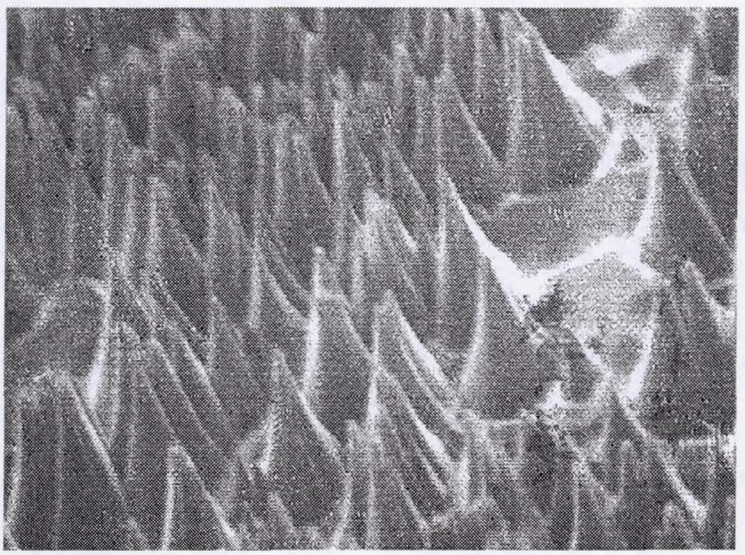

Figure 2b – Typical surface structure of the ion beam textured copper. The structure is composed of cones with heights and bases of 15 μm to 20 μm and 10 μm to 15 μm, respectively.

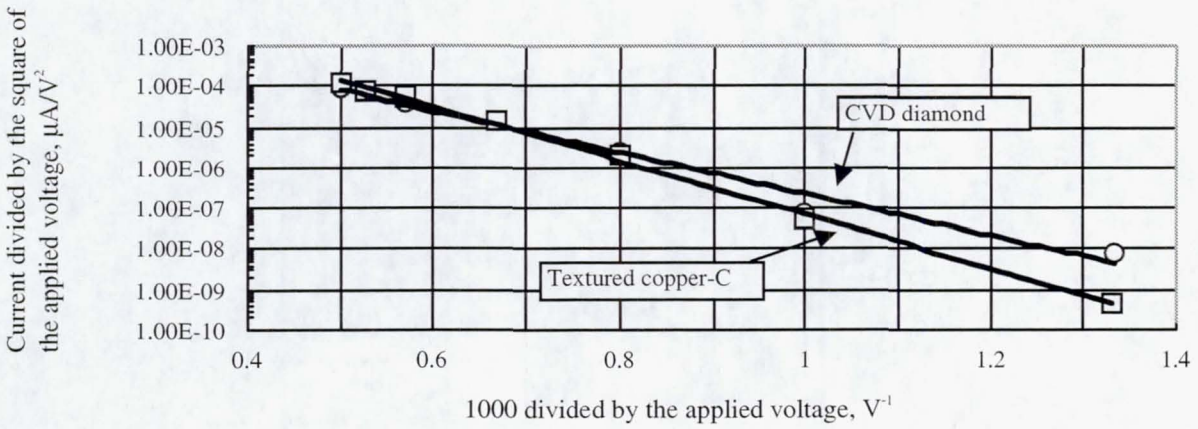

Figure 3 – CVD diamond and textured copper data plotted in Fowler-Nordheim coordinates.

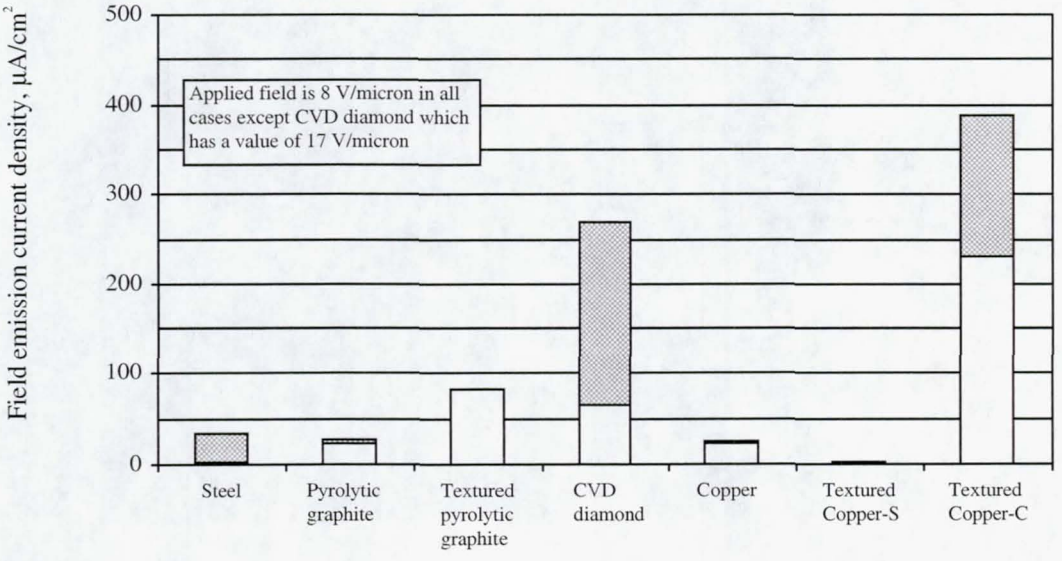

Figure 4 – Field emission current density range for the cathode materials tested in a diode mode. Cross-hatching indicates the variation of current density over the first few hours of life.

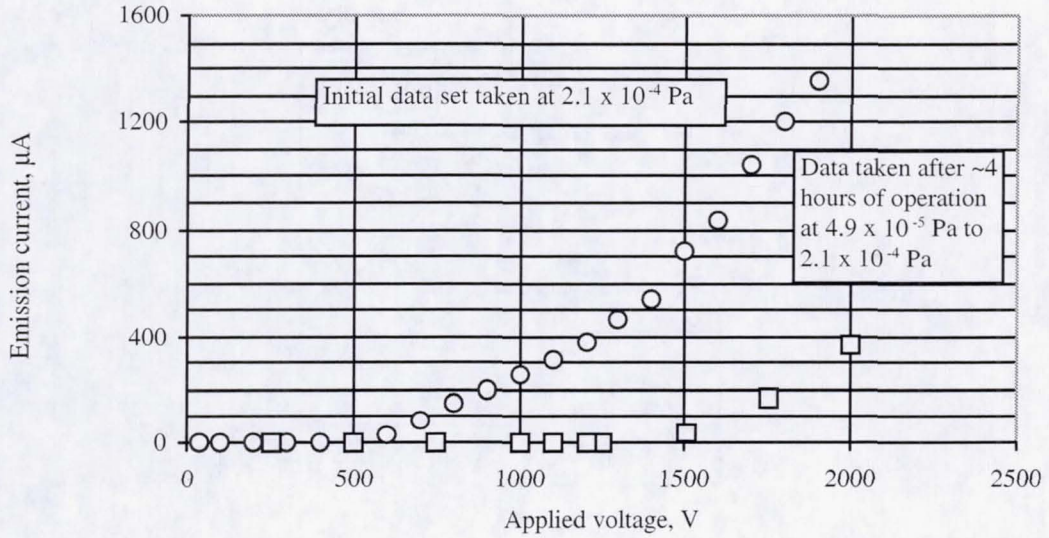

Figure 5 – Current versus voltage for the CVD diamond cathode showing emission current degradation with time.

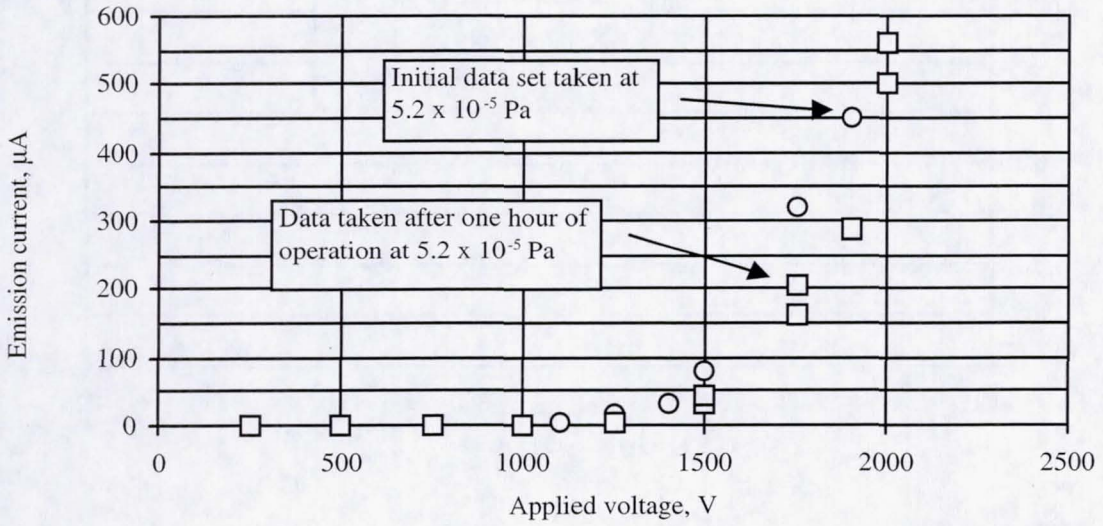

Figure 6 – Current versus voltage for the Textured Copper-C cathode showing emission current degradation with time.

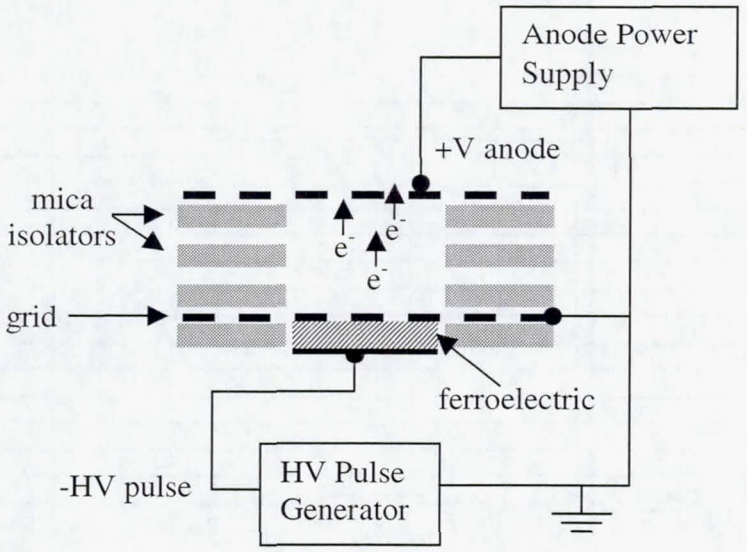

Figure 7 – Schematic diagram of the ferroelectric emission cathode. The top surface of the ferroelectric ceramic is coated with a conducting grid; the bottom surface is coated with a solid conductor. The anode grid is biased +V anode. The anode and ferroelectric grids are separated by mica isolators.

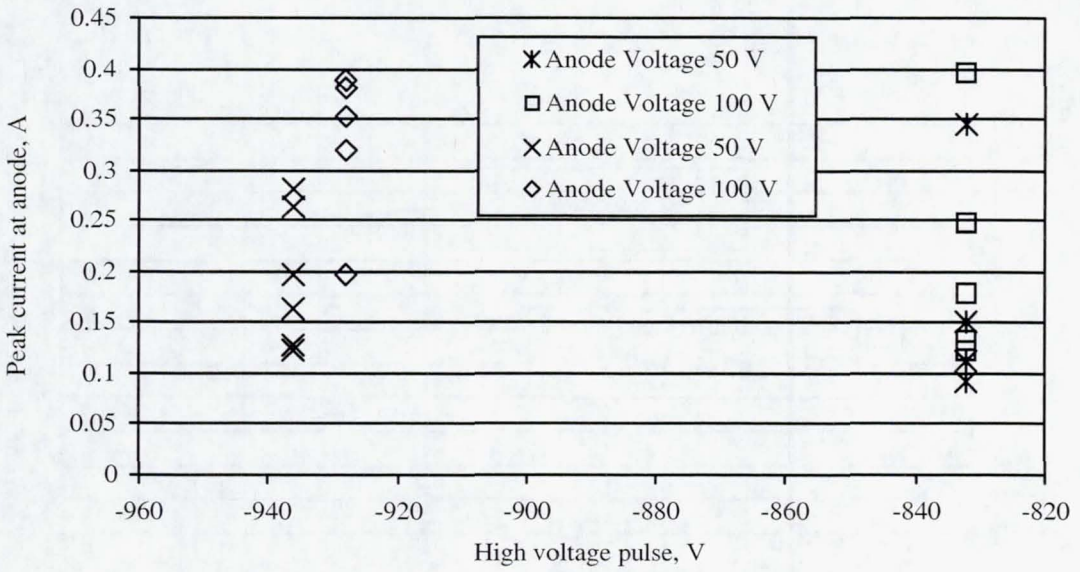

Figure 8 – Initial results of ferroelectric cathode experiments. Electron emission currents measured at the anode for various levels of anode voltage and high-voltage-pulse amplitude.